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# BROADBAND APERIODIC AIR COUPLED ULTRASONIC LENS (PREPRINT)


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**Materials State Awareness & Supportability Branch**
**Structural Materials Division**



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**14. ABSTRACT**
This paper demonstrates the possibility of subwavelength, defined as less than the incident wavelength, broadband focusing in an aperiodic air coupled ultrasonic lens. A near field probe is used to detect well defined resonances from 75 to 125 kHz. The spatial resolution at each of the resonant frequencies is determined and demonstrated to be smaller than the wavelength of the ultrasonic waves. The strongest resonance is observed at 82.9 kHz with a focal spot size of 3.12 mm. The subwavelength spatial resolution of the lens structures at the resonances is attributed to the near field scattering of the acoustic waves.

**15. SUBJECT TERMS**
acoustic lens, air coupled ultrasound, longitudinal waves

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**Byline:** John T. Welter[1,a)], Shamachary Sathish[2)], Josiah M. Dierken[3)], Philip G. Brodrick[4)], Matthew R. Cherry[2)], Jason D. Heebl[5)]

**Abstract.** This paper demonstrates the possibility of subwavelength, defined as less than the incident wavelength, broadband focusing in an aperiodic air coupled ultrasonic lens. A near field probe is used to detect well defined resonances from 75 to 125 kHz. The spatial resolution at each of the resonant frequencies is determined and demonstrated to be smaller than the wavelength of the ultrasonic waves. The strongest resonance is observed at 82.9 kHz with a focal spot size of 3.12 mm. The subwavelength spatial resolution of the lens structures at the resonances is attributed to the near field scattering of the acoustic waves.

**Keywords:** acoustic lens, air coupled ultrasound, longitudinal waves

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Inspired by the research on subwavelength, defined as less than the incident wavelength, focusing hypothesized by Veselago [1] and demonstrated by Pendry [2], several groups are exploring structures with subwavelength features to focus acoustic waves or to achieve acoustic cloaking. Three dimensional and two dimensional periodic [3-13] and aperiodic [14-16] array structures have been designed to achieve subwavelength focusing. Subwavelength resolution in a narrow band frequency range is commonly observed in several of the reported studies [10, 14, 17, 18]. Demonstration over broad frequency ranges has been limited. Li et al used a cylindrical acoustic lens structure to show continuous focusing over the 4.2-7 kHz frequency band with up to $\lambda/4.1$ focusing [8]. However, this lens had focal regions at every demonstrated frequency. Spiousas et al demonstrated a type of broadband tunable resonator based on anisotropic metafluids with a structure consisting of corrugated, periodic cylinders in a fluid [11]. The 3 structures shown operated in the frequency range of 1-5 kHz, with up to 4 clearly defined resonances at which the amplitude of the acoustic pressure was high. An approach using a two dimensional periodic unit cell acoustic lens with a broad bandwidth and a graded refractive index medium was developed and demonstrated by Zigoneanu et al to operate in the range of 1.5-4.5 kHz [12]. Ding et al demonstrated multiband and broadband acoustic structures based on split hollow spheres between 0.9-1.6 kHz [13]. The multiband structure had 3 distinct resonances while the broadband structure had 6 distinct resonances. With the exception of the lens described in Li et al, all the other acoustic lenses had bandwidths in the range of 0.9-5 kHz with very few resonances for evaluation of the spatial resolution. Subwavelength spatial resolution at each of the reported resonant frequencies was not clearly established.

Welter et al recently demonstrated subwavelength focusing of acoustic waves in air using a cylindrical aperiodic structure [19]. Focusing was examined in the frequency range of 80-90

kHz and the average spatial resolution was better than the wavelength by 15%. However, the structure's broadband characteristics were not experimentally investigated. The present paper describes the investigation of the broadband, subwavelength focusing capability of the aperiodic cylindrical acoustic lens in air over the frequency range of 75-125 kHz with higher resolution in the frequency domain.

To measure the spatial resolution of the lens a detector consisting of a 50 μm fiber with a 350 μm diameter metalized polymer film reflector attached is positioned at the center of the lens at a distance of 2.5 mm from the lens surface. This was the experimentally determined distance of maximum pressure. A scanning laser vibrometer is used to measure the response of the detector at several positions across the focal plane. These measurements were taken in a line centered on the focal position spanning a total distance of approximately 14 mm. This corresponds to the central axis of the lens. Figure 1 shows the diameter cross-section of the aperiodic lens structure, computationally derived acoustic pressure at a distance of 1.7 mm from the lens surface (focal plane) at 100 kHz, and experimentally measured acoustic pressure at a distance of 2.5 mm from the lens surface (focal plane) at 82.9 kHz. The computed and experimentally measured acoustic pressures have been normalized to their highest pressures, 0-1 and 0.5-1.5 respectively, for comparison. Although the acoustic lens was optimized to focus at 100 kHz, experimental measurements demonstrate it operates more efficiently at 82.9 kHz. Possible reasons for the differences have been described in detail by Welter et al [19].

The distance between the lens and the detector, 2.5 mm, is less than one wavelength over the frequency range tested, and it is considered the near field. The acoustic pressure across the focal plane varies with the highest amplitude being at the center of the lens, Fig. 1. This acoustic field pattern is similar to theoretically predicted and experimentally observed field patterns in

similar lens structures designed for microwave, optical, and acoustic focusing, reported in the literature [8, 10, 12, 14, 16, 18, 20-22]. The spatial resolution of the lens defined as the width of the experimental pressure versus position curve at 3 dB below the peak, or full width at half maximum (FWHM). At 82.9 kHz, the spatial resolution is 3.12 mm, which is 0.75 of the wavelength of sound in air at the same frequency.

To measure the frequency response of the lens over the range of 75-125 kHz, the detector is positioned at the center of the lens at a distance of 2.5 mm from the lens surface. The amplitude of the acoustic pressure is measured with a scanning laser vibrometer while changing the input to the acoustic transducer placed behind the lens. The pressure at a single point along the center axis of the lens is measured as a function of frequency. Figure 2 shows the experimentally measured acoustic pressure variation with the frequency over 75-125 kHz. The lens response has several resonances in the broad frequency range illustrating the broad band nature of the lens. The acoustic pressure response is strong in 75-90 kHz and 115-125 kHz bands, while in the 90-115 kHz band the response of the lens is confounded by signal noise and low signal amplitude. The resonances are observed to be aperiodic in frequency and have varying widths. Additionally, several resonances appear very close to each other with some partially superimposed and some with very low amplitudes.

The existence of the multiple resonances can be explained qualitatively by considering the lens as a combination of multiple circular rings following the approaches in the literature [11, 23, 24]. Each individual ring can be considered as a separate resonator with its own resonances [11, 23, 24]. Hence, the resonances of the lens are a linear combination of the individual ring resonances. Therefore, it is reasonable to expect the lens to have multiple resonances [11, 23,

24]. It is the combined effect of individual ring resonances that produce the observed high pressure amplitude at the focal point for multiple frequencies.

Clearly defined resonance peaks with pressure amplitudes greater than 9 mPa are analyzed to avoid problems associated with peaks containing overlapping resonances or low amplitudes. The method used previously to determine the spatial resolution at 82.9 kHz is used to determine the spatial resolution at all clearly defined resonances. Figure 3 shows a plot of the spatial resolution of the lens, defined as FWHM, as a function of frequency for all clearly defined resonances in the frequency range of 75-125 kHz. For comparison the ultrasonic wavelength as a function of frequency in air is plotted in the same figure. The parabolic behavior of the ultrasonic wavelength as a function of frequency in air is very well established in far field measurements [25]. However, from the data presented here for near-field subwavelength focusing, this relationship is not valid. The spatial resolution for all the analyzed resonance frequencies is on average 25% higher than the far field wavelength while the distance from the surface of the lens is 73% of the far field wavelength at 100 kHz.

The observed subwavelength spatial resolution at each of the clearly defined resonances is a result of near field diffraction by the lens, and follows from the interaction of incident radiation through a subwavelength aperture [26]. The diffracted components of the evanescent waves carry the subwavelength features of the lens structure [26]. The components of the evanescent acoustic waves combine to produce the acoustic pressure incident on the detector. Evanescent acoustic wave pressure displaces the detector, and those displacements are detected by a scanning laser vibrometer. This measurement set-up is similar in principle to near field scanning probe microscopies such as near field scanning optical microscopy (NSOM), near field evanescent microwave microscopy, ultrasonic force microscopy (UFM) and atomic force

acoustic microscopy (AFAM). In all of these cases, diameter of the probe detecting the evanescent fields determines the spatial resolution rather than the excitation frequency [26]. Based on the operating principles of near field scanning probe microscopy, using a smaller diameter metallic film reflector to detect the acoustic evanescent wave pressure would theoretically provide higher spatial resolution than reported in this work. Furthermore, a smaller probe may help to resolve the overlapping resonant peaks observed in Fig. 2. It is possible that the lens could have different focal distances at each frequency and could show less scatter if the acoustic pressure measurements are performed at distances from the lens optimized for each resonance frequency.

Therefore, the results demonstrate the possibility of focusing ultrasound with subwavelength resolution at multiple frequencies in air over the observed frequency range of 75-125 kHz using a single acoustic lens. The response of the lens shows multiple distinct resonances as well as some which overlap. For the resonances that are clearly separated with strong amplitudes the FWHM have an average spatial resolution 25% better than their corresponding wavelengths. The lens presented has 12 resonances spanning over 40 kHz which is a large bandwidth when compared to acoustic structures presented previously [8, 11-13]. It is possible that larger bandwidths, greater focusing, or longer focal distances could be achieved with further optimization. Developing structures to focus acoustic waves to a tight circular spot in air is important in acoustic imaging. It has the potential to improve the capabilities of scanning acoustic microscopy by enabling high resolution imaging, while eliminating the need for a coupling material. It is expected that subwavelength focusing lenses could significantly enhance the sensitivity of the air coupled ultrasonic nondestructive evaluation while maintaining

the depth of penetration of inspections at low frequency. Applications to acoustic spectroscopy and medical ultrasound fields are foreseen as well.

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**FIGURE CAPTIONS**

Figure 1: Diameter cross-section of the aperiodic lens structure above the x-axis (black-solid, white-air), Solid line: simulated pressure (normalized 0-1) vs. position (mm) across the diameter of the lens at 82.9 kHz and focal distance of 1.7 mm, Square points: experimental pressure (normalized 0.5-1.5) vs. position (mm) across the diameter of the lens at 82.9 kHz and focal distance of 2.5mm

Figure 2: Pressure vs. frequency plot showing the resonances of the lens from 75-125 kHz

Figure 3: Plot of ultrasonic wavelength in air vs. frequency and measured 3 dB full width at half maximum (FWHM) vs. frequency. FWHM represents the spatial resolution of the lens obtained using a 350 μm reflector.

Figure 1

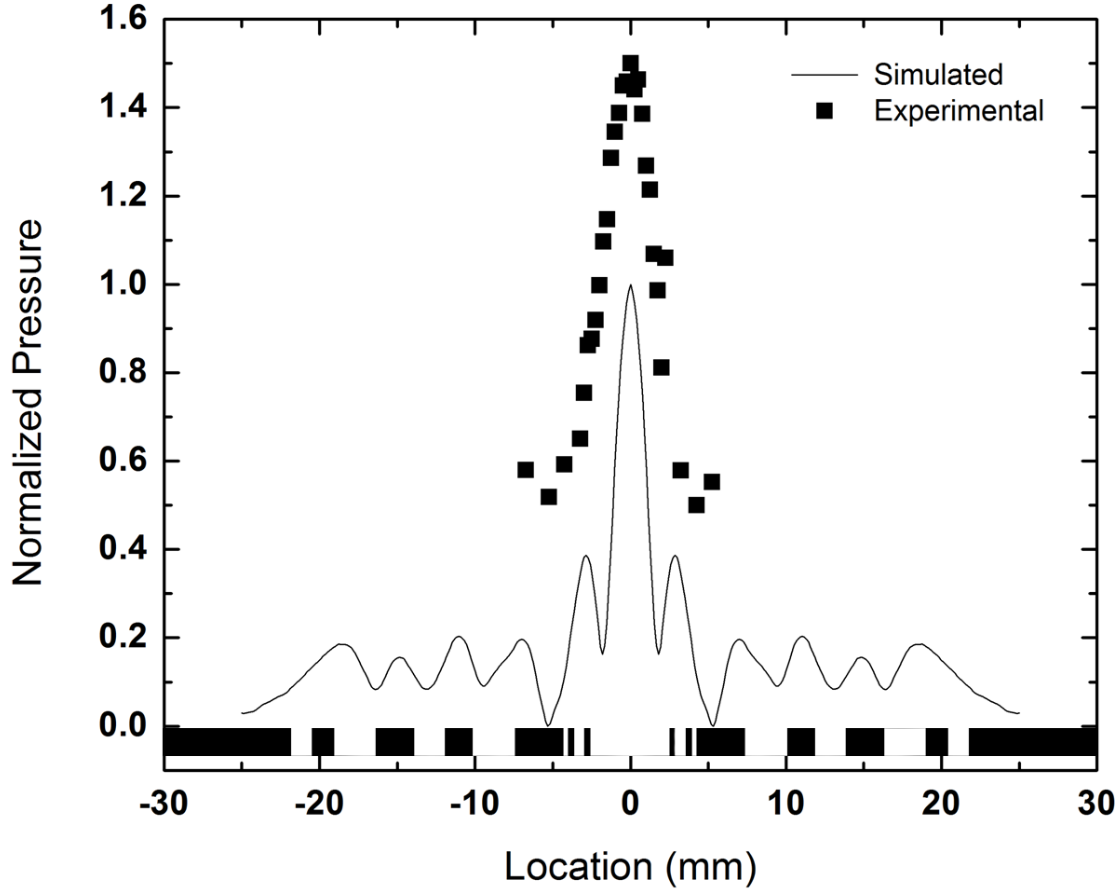

1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Normalized Pressure
-30
-20
-10
0
10
20
30
Location (mm)
Simulated
Experimental

Figure 2

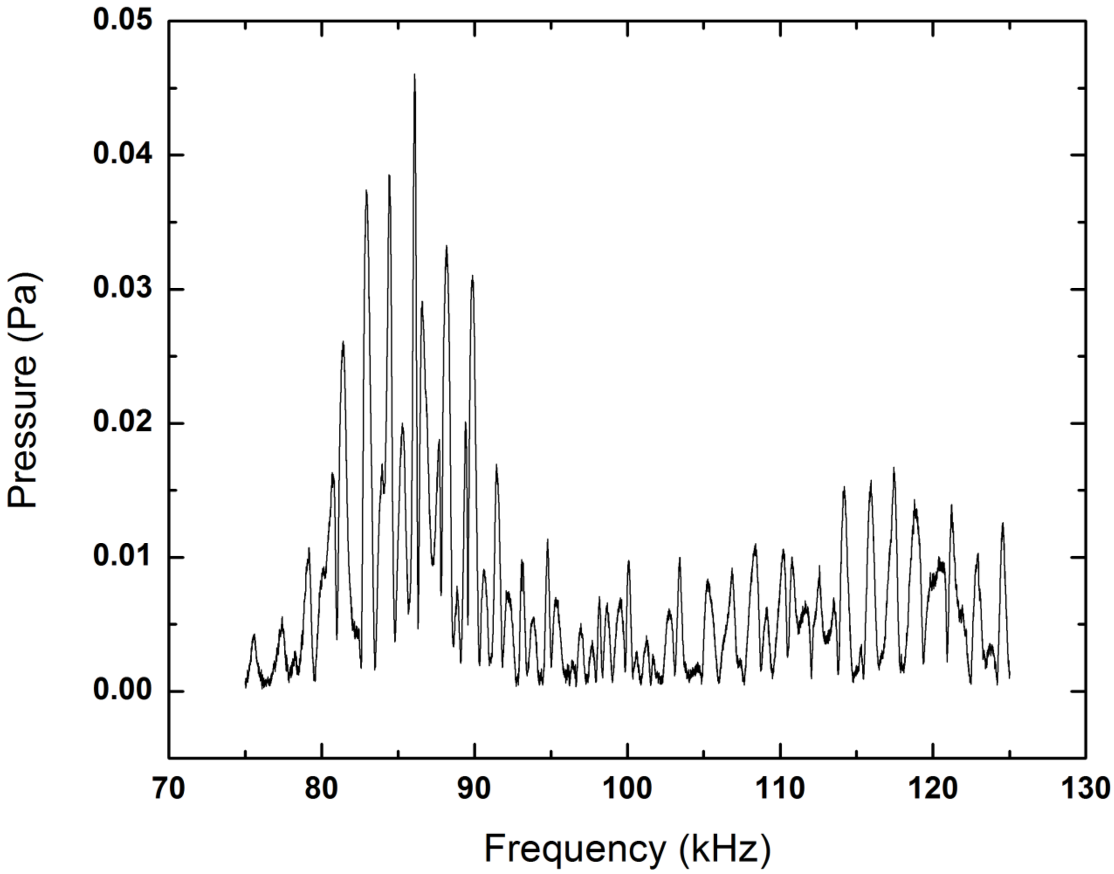
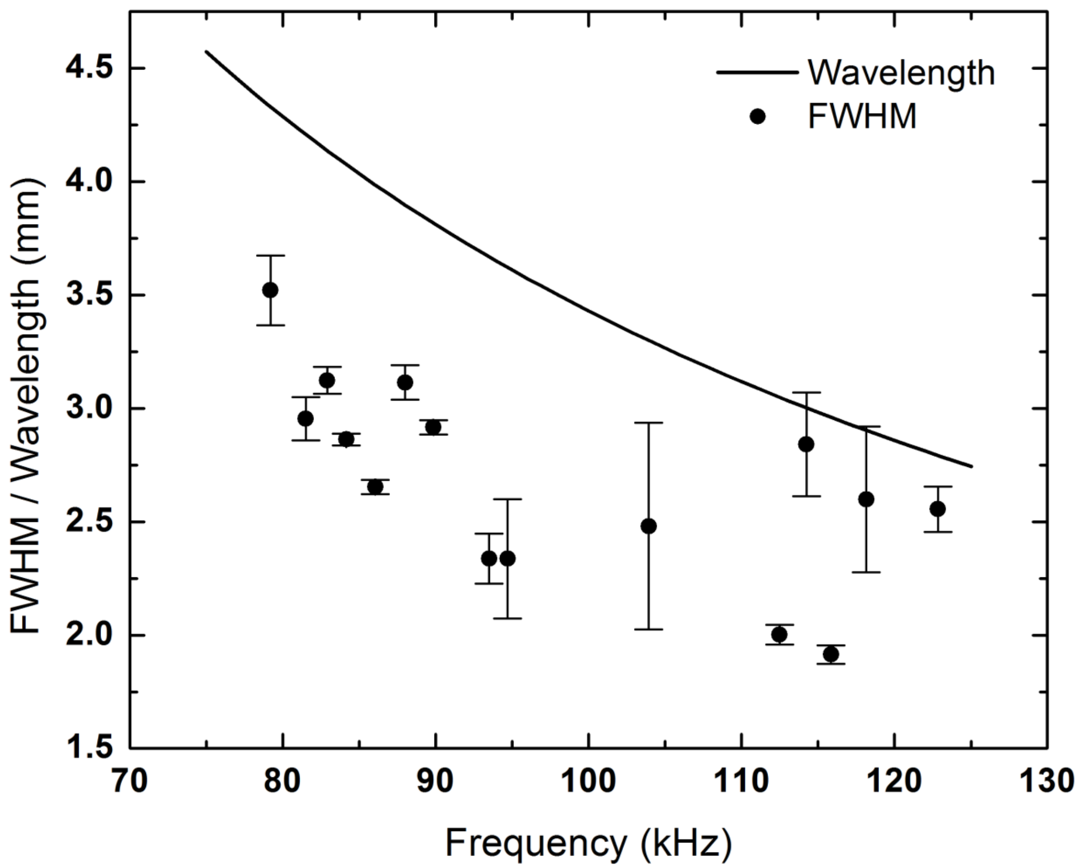

0.05
0.04
0.03
0.02
0.01
0.00
Pressure (Pa)
70
80
90
100
110
120
130
Frequency (kHz)

Figure 3


Wavelength
FWHM
FWHM / Wavelength (mm)
Frequency (kHz)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
70
80
90
100
110
120
130